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Redundant Use of Luminance and Flashing with Shape and Color as Highlighting Codes in Symbolic Displays

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Three visual search experiments evaluated the benefits and distracting effects of using luminance and flashing to highlight subclasses of symbols coded by shape and color. Each of three general shape/color classes (circular/blue, diamond/red, square/yellow) was divided into three subclasses by presenting the upper half, lower half, or entire symbol. Increasing the luminance of a subclass by a factor of two did not result in a significant improvement in search performance. Flashing a subclass at a rate of 3 Hz resulted in a significantly shorter mean search time (48% improvement). Increasing the luminance of one subclass (by a factor of five) while simultaneously flashing another significantly improved search times by 31% and 43% respectively, compared with nonhighlighted search conditions. In each experiment, the search times for nonhighlighted target subclasses were not affected by the presence of brighter and flashing targets. The failure of the initial experiment to find a significant performance improvement caused by increasing symbol luminance suggested that a larger luminance increase was necessary for this code to be effective. The overall results suggest that using luminance and flashing to highlight subclasses of color- and shape-coded symbols can reduce search times for these subclasses without producing a distraction effect by way of a concomitant increase in the search times for unhighlighted symbols.

INTRODUCTION

The literature on basic visual search performance has sufficiently demonstrated that simple feature searches for color (e.g., blue target among red distractors) are extremely efficient and practically independent of the number of distractor stimuli used, whereas search performance for shape variants is not as efficient (for review, see Davidoff, 1987; Treisman, 1986; Treisman and Gelade, 1980). Furthermore, numerous experiments have established that the redundant addition of color to geometric symbol shapes in visual displays significantly decreases search time and increases accuracy (Christ, 1975; Jacobsen, Neri, and Rodgers, 1985; Jacobsen, Rodgers, and Neri, 1986; Jubis and Turner, 1988). Several studies (Davidoff, 1987;

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Gummerman, 1975; Jubis, 1990) have noted that using color to redundantly code display symbols results in dramatically improved search performance and is suggestive of a parallel processing capability for color. This differs from the less efficient processes that guide visual search performance when shape coding is used exclusively. Within a general shape/color class of symbols there may be subclasses of symbols represented by some deviation or partial representation of the symbol geometry. In these cases, results from several studies (Jacobsen et al., 1985, 1986; Jubis, 1990) have indicated that search performance under a partially redundant scheme is determined primarily by the ability to process the shape variations within a general shape/color class, whereas the color of the overall target class serves to effectively exclude nontarget symbols.

Coupled with the complex information presented by most visual displays, these results have generated considerable interest in determining what other stimulus dimensions can be added to color-coded symbols in order to extract and highlight additional subclass information in a hierarchical manner. The goal is to add some other stimulus code to highlight the subclass while preserving the general shape and color association of a shape variant subclass with its overall group. Some candidates for redundant coding, such as luminance and flashing, are suggested by the literature on conjunctive visual search. Although a number of studies (Duncan and Humphreys, 1989; Treisman, 1991; Treisman and Gelade, 1980; Wolfe, Cave, and Franzel, 1989) have demonstrated that visual search typically becomes less efficient when feature dimensions are conjoined (e.g., subject searches for a red circle among blue circles and red squares), there are some notable exceptions. Nakayama and Silverman (1986) observed that searches for conjunctions of depth with color yielded Reaction Time × Display Item Density functions that were virtually flat, indicating a highly efficient, parallel, visual search process. In their task, the subjects searched for a red front plane or blue back plane target among red back and blue front plane distractor stimuli. Similarly parallel search performance has been found for conjunctions of movement and shape (McLeod, Driver, and Crisp, 1988). Although depth might be a good candidate as an additional code, movement would be inappropriate for most symbolic displays because of static positional requirements.

However, a fundamental construct of motion is temporal modulation, and thus symbol flashing might be an ideal subclass highlighting code. The use of flashing elements within a visual display has been demonstrated to be a highly effective way of attracting attention (Crawford, 1963; Goldstein and Lamb 1967; Newman and Davis, 1961; Smith and Goodwin, 1971, 1972; Thackray and Touchstone, 1991). However, there has been a general consensus among display designers and researchers (Heglin, 1973; Smith and Goodwin, 1972; Thackray and Touchstone, 1991) that flashing should be used exclusively as a warning or alert signal, for fear that the distraction caused by the routine use of such an attentionally demanding signal would be great. Although Smith and Goodwin (1971) considered—and rejected—the possibility that flashing some display elements might distract observers who were attempting to search for nonflashing elements, the display used in that experiment was alphanumeric, not symbolic, and flashing was not used in a redundant manner with any existing information code.

However, Thackray and Touchstone (1991) redundantly coded shape and flashing in a simulated air traffic control scenario. Subjects searched for intruding aircraft (shape-coded to indicate that they lacked the required transponding equipment for the

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Three visual search experiments evaluated the benefits and distracting effects of using luminance and flashing to highlight subclasses of symbols coded by shape and color. Each of three general shape/color classes (circular/blue, diamond/red, square/yellow) was divided into three subclasses by presenting the upper half, lower half, or entire symbol. Increasing the luminance of a subclass by a factor of two did not result in a significant improvement in search performance. Flashing a subclass at a rate of 3 Hz resulted in a significantly shorter mean search time (48% improvement). Increasing the luminance of one subclass (by a factor of five) while simultaneously flashing another significantly improved search times by 31% and 43% respectively, compared with nonhighlighted search conditions. In each experiment, the research times for nonhighlighted target subclasses were not affected by the presence of brighter and flashing targets. The failure of the initial experiment to find a significant performance improvement caused by increasing symbol luminance suggested that a larger luminance increase was necessary for this code to be effective. The overall results suggest that using luminance and flashing to highlight subclasses of color- and shape-coded symbols can reduce search times for these subclasses without producing a distraction effect by way of a concomitant increase in the search times for unhighlighted symbols.

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airspace) while monitoring the distances between and operational characteristics of the numerous aircraft presented on the screen. The intruding aircraft could be redundantly coded with color, flashing, or both. Thackray and Touchstone found that flashing led to significant improvements in the ability of subjects to respond to the trespassing aircraft, but they cautioned that flashing could distract the operator if it remained on the display and was used for other than warning purposes. However, no experiment has explicitly examined the potentially distracting effects of flashing items within a symbolic display format.

Another possible highlighting code is luminance. Previous research has indicated that modifying symbol luminance might be an effective way of redundantly coding shape or color in symbolic displays. Eriksen (1952, 1953) varied stimulus shape, hue, brightness, and size and reported that multicoded stimuli generally led to faster search times than did unidimensional stimuli. However, those experiments were primarily designed to measure the effects of adding more dimensions to target and nontarget stimuli on search performance, and they did not address the issue of whether or not interference from highlighted symbols decreased search performance of unhighlighted symbols. Furthermore, Eriksen (1953) used Munsell chips on a cardboard shape to code hue and lightness, making comparisons with self-luminous colored shapes difficult.

Newman and Davis (1961) also investigated the dimensions of hue, brightness, and flashing in a detection task using a projection display to produce self-luminous symbols. They found that color was particularly beneficial to search performance, but their study is of limited relevance to the present study because in all conditions coding was nonredundant with symbol shape; there was never a redundant coding pattern to which the subject could become accustomed. Furthermore, Newman and Davis never combined levels of brightness with three levels of color, and they also used a very large number of distinct symbols shapes (36) in their display.

To mitigate the confounding presented by the Newman and Davis design and, more importantly, to clarify the role of redundancy with luminance, Van Orden, DiVita, and Shim (1990) studied the relationship between three hues (red, blue, and yellow) and the three levels of symbol luminance by redundantly and nonredundantly combining the dimensions in diamond-shaped symbols on a cathode ray tube (CRT). Subjects' search performance was degraded when hue and luminance were nonredundantly coded; however, interference was predominantly evident in searches for symbols of the middle-luminance level. These results suggested that brightness might be a suitable code for highlighting a group subset, provided that only two mutually distinguishable luminance steps be used on a display.

Thus the issues addressed by the following experiments were (a) whether or not the additional redundant coding of color/shape symbol subclasses with increased luminance and flashing would significantly improve visual search performance and (b) whether or not highlighting a subclass would cause distraction and lead to a deterioration in the search performance of unhighlighted subclasses.

EXPERIMENT 1: EFFECT OF LUMINANCE HIGHLIGHTING

As noted, results from our laboratory (Van Orden et al., 1990) suggested that luminance highlighting might be effective if luminance was constrained to two levels. Thus the present set of experiments examined the use of luminance as an additional code to highlight subclasses of general shape/color symbol categories. It was assumed that the addition of luminance to a subclass would improve visual search performance.

Method

Subjects. Eleven subjects (seven men, four women) voluntarily participated. They ranged in age from 22 to 35 years. All reported normal color vision, and those subjects who wore corrective lenses did so during the experiment.

Materials and apparatus. A Ramtek 9400/91 graphics generator and display system was controlled by a Digital Equipment Corp. VAX 730 computer. A 48.3 cm (diagonal) color CRT display had a pixel resolution of 1280 × 1024 pixels. The CRT monitor was calibrated with a Photo Research SpectraScan spectral radiometer. Responses were made via a four-choice response panel. Diamond-shaped, square, and circular symbols of double pixel width were 0.5 cm in length on each edge (approximately 0.4 deg visual angle). Diamond-shaped symbols were always red, whereas circular and square symbols were always blue and yellow, respectively. The 1976 CIE chromaticity specifications (u′, v′, cd/m^2) of the stimuli were as follows: red (0.427, 0.531, 2.26 cd/m^2), blue (0.173, 0.179, 1.04 cd/m^2), yellow (0.264, 0.547, 1.74 cd/m^2). The luminances of the stimuli were determined by adjustment to appear equally bright and saturated.

Procedure. On each trial, subjects viewed a geographical plot of an ocean and land (outlined in green), as shown in Figure 1. This portion of the CRT screen measured 17 × 16 cm. Vertical and horizontal lines divided the screen into four quadrants. Each geographical "screen" contained 36 symbols, equally divided into each quadrant. There were three general symbol classes (red/diamond, blue/circular, yellow/square), each represented by 12 symbols. The 12 symbols of each class were further divided evenly into three groups: 4 top-half symbols, 4 whole symbols, and 4 bottom-half symbols.

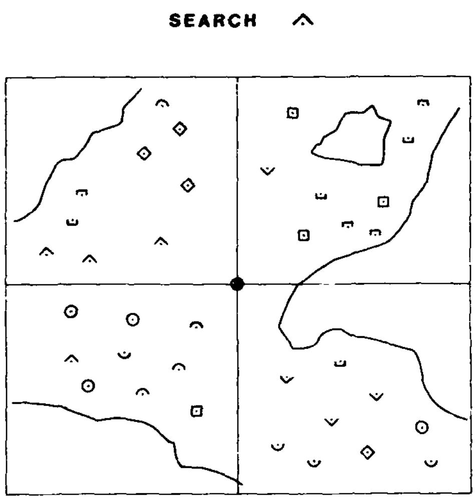

Figure 1. *A representative screen from the experiments. General symbol shape/color classes were circular (blue), square (yellow), and diamond shaped (red). Within each general class were three subclasses composed of either the entire symbol or its upper or lower half. There were always equal numbers of each class and its subclasses. Land masses and plot perimeter were outlined in green; quadrant boundaries were gray.*

Two general display configurations were delineated with the highlighting of the red/diamond upper half ("red hats") subgroup of the red/diamond symbols. The luminance of the red hat symbols was increased from 2.26 to 4.90 cd/m^2 under the highlighted display configuration. Within each of these display configurations, subjects completed blocks of trials in which they searched for red hat, upper-half blue/circular (blue hat), and upper-half yellow/square (yellow hat) symbols. The search goal was written over the top of the plot, instructing the subject to locate the quadrant of the plot with the greatest number of red, blue, or yellow hat-shaped symbols.

In all, 69 random symbol distributions were available for the experimental paradigm. Each distribution was randomly selected for each individual trial, with the restriction that the same distribution never appear twice in succession. The symbol distributions were superimposed on one of three land/sea maps. No subject ever reported remembering a particular plot. This procedure ensured a relatively even distribution of symbols across each plot; the displays always contained 9 symbols in each quadrant. Although clusters and groupings of symbols are more likely encountered in real life, Carter (1982) has demonstrated that target items located outside of clusters are located significantly faster than are those within clusters. Additionally, he found that items within clusters are found no more quickly than items distributed on a random display. Thus the present methodology avoided the reaction time disparity associated with clustered display configurations.

Within each of the highlighted and unhighlighted display configurations, a block of 20 trials was completed for each of the specific red, blue, and yellow hat search conditions. Blocks of 20 trials were also run in an additional "search-all-hats" condition within each of the highlighted and unhighlighted configurations. The first five search reaction times within each target search block were not recorded. For each of the specific red, blue, and yellow hat searches, the number of target symbols in a given quadrant could vary from 2 to 4. In the search-all-hats conditions, the number of target items per quadrant ranged from 5 to 9. Search conditions were randomized, the first search block was always repeated at the end of the session, and the responses made during the entire first block of trials were ignored. Subjects were instructed to minimize mistakes and then to work on minimizing search time. Feedback for incorrect responses was provided by a tone at the end of a trial. A break was provided in the middle of the experiment.

Results and Discussion

The mean of the search reaction times and the average number of correct responses were calculated for each search condition for every subject. The reaction time data were submitted to a repeated-measures analysis of variance (ANOVA) procedure with three levels of specific targets (red, blue, and yellow hats) within two levels of display configuration (unhighlighted red hats, highlighted red hats). A significant Specific Targets × Display Configuration interaction was found, $F(2,20) = 4.57$, $p < 0.05$. A post hoc pairwise comparison of the target search times (using the Tukey honestly significant difference [HSD] procedure) indicated that the average search time for the brighter red hat stimuli was significantly shorter than the search times for the yellow hat stimuli from both display conditions ($p < 0.05$). Figure 2 displays the target search times. There was no significant search time difference between the two global search-all-hats conditions (delineated by the presence or absence of red-hat highlighting), as examined by a simple t test. The search-all-hats data are also presented in Figure 2.

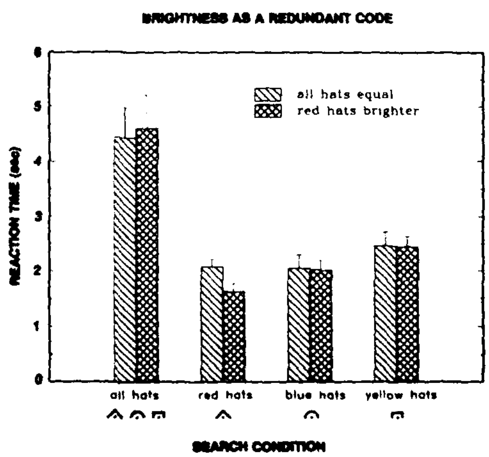

Figure 2. *Mean search reaction times as a function of search condition for the experiment in which brightness was added to a subclass of one general shape class. Error bars represent one standard error from the mean.*

A repeated-measures ANOVA on the number of correct responses yielded only a main effect of specific target type, collapsed across the display configurations, $F(2,20) = 5.73$, $p < 0.05$. A Tukey HSD test ($p < 0.05$) indicated that the yellow hat stimuli, regardless of highlighting, had a lower mean number of correct responses than did the blue and red hats (14.64, 14.41, and 13.32 out of a possible 15.0 for red, blue, and yellow hat stimuli, respectively).

Although luminance highlighting led to a search time improvement in excess of 20%, the result failed to reach statistical significance. However, the trend in the data suggests that a larger luminance step might significantly improve search times for the highlighted symbols, as is addressed in Experiment 3. The reason for the lower discriminability of the yellow hat stimuli was not clear. It might be that the difference between the upper, lower, and entire yellow/square symbol configurations may not have been as discriminable for the square symbols as for the diamond-shaped or circular symbols. The effect was not observed in either of the following experiments.

EXPERIMENT 2: EFFECT OF FLASHING

As noted, although blinking and flashing display items have been recognized as potent and attentionally demanding stimuli (Crawford, 1963; Goldstein and Lamb, 1967; Newman and Davis, 1961; Smith and Goodwin, 1971, 1972), there has been concern over their routine use in displays for fear that flashing can cause undue distraction; therefore it has been suggested that flashing should be used only for warning and alert purposes (Thackray and Touchstone, 1991). However, no experiment has explicitly examined the potentially distracting effects of flashing items within a symbolic display format. It was precisely that issue which Experiment 2 attempted to address. Under some situations, could flashing be used to redundantly code display symbols without creating unwanted distraction?

Methods

Subjects. Ten subjects (five men and five women) ranging in age from 22 to 35 years voluntarily participated in the experiment. Nine of the ten had participated in Experiment 1. All reported normal color vision, and those subjects who wore corrective lenses did so during the experiment.

Apparatus and procedure. Experiment 2 was identical to Experiment 1, with the following exceptions. The red hats were highlighted by flashing (at a rate of 3 Hz) instead of making them brighter. Gerathewohl (1954) has demonstrated that the conspicuity of a flashing signal is virtually equivalent over a flash-rate range from 1 to 4 Hz.

Subjects completed blocks of trials in which they searched for an inverted red hat symbol in order to assess the potential for interference from flashing red hats on symbols within the same general shape/color category. The inclusion of a block of trials for the inverted red hat symbol brought the total number of search blocks to 11: 1 for each of the specific subclass hat searches under each display configuration, a search of all hats under flashing and nonflashing conditions, and the initial block, which was repeated later in the block sequence.

Results and Discussion

The mean of the search reaction times and the average number of correct responses were calculated for each search condition for every subject. A repeated-measures ANOVA on reaction times for specific target searches yielded a significant Specific Targets × Display Configuration interaction, $F(3,27) = 8.32$, $p < 0.001$, and significant specific targets and display configuration main effects, $F(3,27) = 12.60$, $p < 0.001$; $F(1,9) = 27.15$, p

< 0.001. The data are presented in Figure 3. Subsequent pairwise comparisons indicated that the mean search time for the flashing red hat symbols was significantly faster than all other mean search times (Tukey HSD, $p < 0.05$). Additionally, a t test indicated that red hat flashing had no significant effect on the search times of the two search-all-hats conditions.

Although a specific targets within display configuration repeated-measures ANOVA for the number of correct responses for the specific target searches data yielded a significant main effect of specific targets, $F(3,27) = 3.49$, $p < 0.05$, the Tukey HSD post hoc analysis failed to reveal any significant differences among the means (which ranged from 14.20 to 14.70).

As expected, using flashing to highlight a subclass of symbols led to a dramatic 48% improvement in search reaction times compared with the nonflashing condition, and this is consistent with previous research (Crawford, 1963; Goldstein and Lamb, 1967; Newman and Davis, 1961; Smith and Goodwin, 1971, 1972; Thackray and Touchstone, 1991). Contrary to the expectation that flashing a subset of display symbols might distract observers and make searching for nonflashing symbols more difficult (Thackray and Touchstone, 1991), the results of the present study indicated that redundantly coding a symbol subclass with flashing had virtually no effect on the search performance for nonflashing symbol subclasses.

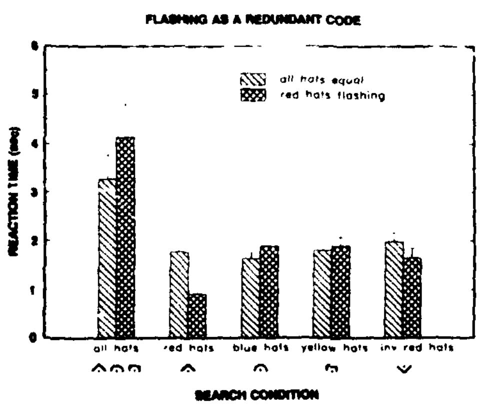

Figure 3. *Mean search reaction times as a function of search condition for the experiment in which flashing was used as a highlighting code.*

EXPERIMENT 3: DUAL HIGHLIGHTING

The results of Experiment 2 demonstrated that flashing could be used effectively to redundantly code subclasses of more global shape- and color-coded symbols. The improvement in search time for highlighted symbols was without concomitant changes in the search times of unhighlighted subclasses. Furthermore, the trend in the results of Experiment 1 suggested that a larger increase in luminance might make the highlighted subclass more salient, which could lead to significantly faster search times. Thus the final experiment sought to determine whether or not brightness and flashing could be used simultaneously to highlight two different subclasses. Two familiar questions were addressed: Would search time improvements be observed when two highlighting schemes were used simultaneously? Would some form of interference or distraction, by way of slower reaction times to unhighlighted symbol subclasses, emerge under the dual highlighting display configuration?

Methods

Subjects. Eleven subjects (three men, eight women), ranging in age from 22 to 35 years voluntarily participated. Five of the 11 had not participated in either Experiments 1 or 2. All reported normal color vision, and those subjects who wore corrective lenses did so during the experiment.

Apparatus and procedure. The equipment for Experiment 3 was the same as that in Experiments 1 and 2. The procedure was identical to that used in Experiment 2, except that when the red hats were redundantly coded with 3 Hz flashing, the luminance of the blue hat stimuli was raised from 1.04 cd/m^2 to 5.41 cd/m^2.

Results and Discussion

The repeated-measures ANOVA on mean reaction times for specific target searches yielded a significant Specific Targets × Display Configuration interaction, $F(3,30) = 9.38$, $p < 0.001$, and significant specific targets and display configuration main effects, $F(3,30) = 9.11$, $p < 0.001$; $F(1,10) = 49.94$, $p < 0.001$. Figure 4 displays the search time data. A Tukey HSD test indicated that, although the reaction times to flashing red hat and brighter blue hat symbols did not differ from one another, their search times were significantly faster than those of all other symbol subclasses tested ($p < 0.05$). The effectiveness of the highlighting codes was dramatic; flashing resulted in a 43% search time improvement, and brightness improved search times by 31%. There was no difference in search speed in the overall search-all-hats condition as a function of display configuration. Additionally, a repeated-measures ANOVA on the number of correct responses

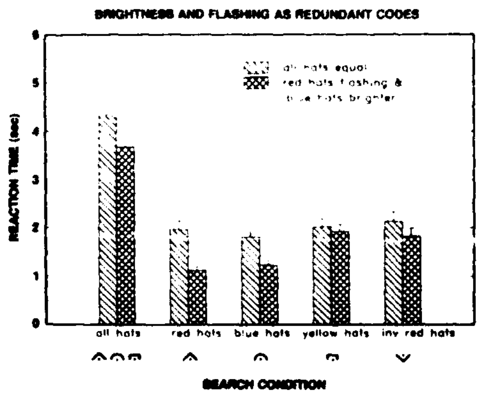

Figure 4. *Mean search times for the experiment in which red hats were highlighted by flashing and blue hats were simultaneously highlighted by brightness.*

for each condition yielded no significant main effects or interactions. The relative consistency of the number of correct responses under the various conditions signaled a successful adoption by the subjects of the instructed strategy of minimizing mistakes, and then minimizing search time.

The experiment demonstrated that luminance and brightness effectively highlighted subclasses of general shape/color symbols without causing any distraction. The difference between Experiments 1 and 3 in the effectiveness of luminance as a highlighting code probably lies in the size of the luminance step: the red hat stimuli of Experiment 1 were increased in luminance by a factor of two, whereas the blue hats of Experiment 3 were increased in luminance by a factor of five. Thus the effectiveness of a luminance code for highlighting is probably dependent on the baseline luminance of the symbols on the screen and the size of the luminance increase, up to some asymptote.

CONCLUSIONS

In addition to the observed improvements in search performance for flashing targets or targets of increased luminance, perhaps the most surprising aspect of the results was the absence of highlight-related interference on nonhighlighted targets. We expected some interference to occur when a subclass of targets was made to flash. Thackray and Touchstone (1991) argued against the use of flashing for other than a warning/alert signal because of the apparent potential for distraction. However, many subjects reported that flashing and brighter targets were not distracting, and during searches for nonflashing targets, flashing targets actually served to guide attention toward the nonflashing targets. Indeed, there was no indication, even in the form of a trend in the data, that any form of interference was taking place under the highlighted display conditions. A similar effect was observed by

Smith and Goodwin (1971), who surmised that flashing could serve as an inclusion or exclusion code.

The improvements in search times for targets highlighted by flashing implies an extremely efficient search capability, on par with search performance previously observed for coding with hue (Davidoff, 1987; Gummerman, 1975; Jubis, 1990; Treisman and Gelade, 1980). Based on the results of numerous visual search experiments, Treisman (1986) has noted that color, size, contrast, tilt, movement, and depth form a select group of fundamental features that are extracted very early in visual processing and give rise to effortless search. The results of the present study suggest that temporal modulation is of the same class as those features listed above. Furthermore, it appears that many of these fundamental features can be used to embellish any symbol set within certain display constraints. Studies by Van Orden et al. (1990) on brightness and Newman and Davis (1961) on flashing indicate that search efficiency is dictated by the number of levels that are used within a particular stimulus dimension. The use of more than one brightness level, flash rate, or depth plane would probably lead to poorer search performance, though this remains to be explicitly tested.

The benefits of highlighting with luminance and flashing demonstrated in the present study may need to be qualified with regards to the conditions under which these codes will remain effective. The restricted luminance range of color monitors, coupled with the effects of ambient lighting and glare on perceived stimulus brightness and contrast on CRT screens, clearly limits the utility of brightness as a highlighting code at present. Of relevance to flashing, some evidence suggests that display elements with abrupt onsets can "capture" attention in a nearly automatic manner (Jonides and Yantis, 1988; Yantis and Johnson, 1990). In the paradigm used in our experiments, subjects were able to effectively filter out the flashing items. In a vigilance or multitask situation, individuals might not be so successful in allocating attention toward unhighlighted items, and highlighting-induced interference could emerge. Clearly, research is required which utilizes real-world tasks (e.g., Thackray and Touchstone's 1991 air traffic control scenario) before the conclusions drawn under the present conditions can be universally accepted.

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REFERENCES

Carter, R. C. (1982). Visual search with color. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 127–136.

Christ, R. E. (1975). Review and analysis of color-coding research for visual displays. *Human Factors, 17*, 542–570.

Crawford, A. (1963). The perception of light signals: The effect of mixing flashing and steady irrelevant lights. *Ergonomics, 6*, 287–294.

Davidoff, J. (1987). The role of color in visual displays. In D. Osborne (Ed.), *International reviews of ergonomics* (Vol. 1, pp. 24–42). London: Taylor & Francis.

Duncan, J., and Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*, 433–458.

Eriksen, C. W. (1952). Location of objects in a visual display as a function of the number of dimensions on which the objects differ. *Journal of Experimental Psychology, 44*, 56–60.

Eriksen, C. W. (1953). Object location in a complex perceptual field. *Journal of Experimental Psychology, 45*, 126–132.

Gerathewohl, S. J. (1954). Conspicuity of flashing light signals of different frequency and duration. *Journal of Experimental Psychology, 48*, 247–251.

Goldstein, D. A., and Lamb, J. C. (1967). Visual coding using flashing lights. *Human Factors* 9, 405–408.

Gummerman, K. (1975). Successive processing of color and form from brief visual displays. *Perceptual and Motor Skills, 40*, 31–41.

Heglin, H. J. (1973). *NAVSHIPS display illumination design guide: Section II. Human factors* (NELC Tech. Doc. 223). San Diego, CA: Naval Electronics Laboratory Center.

Jacobsen, A. R., Neri, D. F., and Rodgers, W. H. (1985). *The effects of color-coding in GEOSIT displays I: Color as a redundant code* (NSMRL Tech. Report 1061). Groton, CT: Naval Submarine Medical Research Laboratory.

Jacobsen, A. R., Rodgers, W. H., and Neri, D. F. (1986). *The effects of color-coding in GEOSIT displays II: Redundant versus non-redundant color-coding* (NSMRL Tech. Report 1069). Groton, CT: Naval Submarine Medical Research Laboratory.

Jonides, J., and Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception and Psychophysics, 43,* 346–354.

Jubis, R. M. T. (1990). Coding effects on performance in a process control task with uniparameter and multiparameter displays. *Human Factors, 32,* 287–297.

Jubis, R. M. T., and Turner, D. (1988). *The effectiveness of redundant color coding on search and identification in a process control task* (DCIEM Tech. Report 88-RR-9). North York, Ontario: Defense and Civil Institute of Environmental Medicine.

McLeod, P., Driver, J., and Crisp, J. (1988). Visual search for a conjunction of movement and form is parallel. *Nature, 332,* 154–155.

Nakayama, K., and Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature, 320,* 264–265.

Newman, K. M., and Davis, A. K. (1961). *Multidimensional nonredundant encoding of a visual symbolic display* (NEL Tech. Report 1048). San Diego, CA: Navy Electronics Laboratory.

Smith, S. L., and Goodwin, N. C. (1971). Blink coding for information display. *Human Factors, 13,* 283–290.

Smith, S. L., and Goodwin, N. C. (1972). Another look at blinking displays. *Human Factors, 14,* 345–347.

Thackray, R. I., and Touchstone, R. M. (1991). Effects of monitoring under high and low taskload on detection of flashing and colored radar targets. *Ergonomics, 34,* 1065–1081.

Treisman, A. (1986). Features and Objects in visual processing. *Scientific American, 255*(11), 114B–125.

Treisman, A. (1991). Search, similarity, and integration of features between and within dimensions. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 652–676.

Treisman, A., and Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12,* 97–136.

Van Orden, K. F., DiVita, J., and Shim, M. (1990). *Preliminary investigation on the utility of saturation and brightness as redundant and non-redundant codes with hue in tactical displays* (NSMRL Report 1161). Groton, CT: Naval Submarine Medical Research Laboratory.

Wolfe, J. M., Cave, K. R., and Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 419–433.

Yantis, S., and Johnson, D. N. (1990). Mechanisms of attentional priority. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 812–825.